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In the future when the DCS becomes predominantly digital, employing time division multiplexing and/or switching, a system timing capability must be provided. In a complex digital DCS under wartime conditions, timing is difficult to achieve. As a basis to evaluate the effectiveness of different timing approaches, a set of desired attributes is needed. Suggested attributes with reasons for each are given.

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IN A DIGITAL DCS

July 1980

Prepared by:

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for Engineering Programs

FOREWORD

The Defense Communications Engineering Center Engineering Publications (EP's) are published to provide engineering guidance to DoD Departments/Agencies and their contractors engaged in engineering, RDT&E, procurement, installation, testing, acceptance, and O&M of specific DCS Projects and Programs. Before using EP's as, or as part of, procurement specifications, coordination should be accomplished with DCEC or the cognizant DCA Program Office to insure currency and the propriety of the application.

Comments or technical inquiries concerning this document are welcome, and should be directed to:

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EXECUTIVE SUMMARY

At some time in the future, the DCS is expected to employ synchronous digital communications networks. Loss of satisfactory timing (synchronization) in such a network can be catastrophic, resulting in all received information being meaningless until satisfactory timing (synchronization) is restored.

This problem has been studied by DCA and its contractors for several years. A large number of approaches have been identified and their characteristics evaluated. All of these approaches can provide communications system timing when they are functioning normally, but a military system supporting full-scale war is expected to encounter severe conditions under which such a normal situation would be short lived. Many of the timing approaches are unacceptable for wartime DCS use.

This publication presents a set of desired attributes against which the different approaches to DCS timing can be evaluated, and explains the need for each attribute. The emphasis is on the ability to support full-scale war.

Technical possibilities for synchronizing a digital DCS have been discussed previously, where it was shown that providing the attributes presented here is both technically and economically practical for the DCS.

Stated very briefly, the attributes provide for keeping major nodes of the DCS within acceptable phase tolerances of one another by automatically coordinating all of their phases with the standard provided by the U.S. Naval Observatory, UTC(USNO), or the National Bureau of Standards, UTC(NBS), whenever either is available. If UTC is not available, a particular clock within the DCS is automatically selected as the reference for the rest of the network. Survivability of the network is further enhanced by: (1) assuring that it is not dependent on any one point of centralized or concentrated vulnerability to enemy action, (2) providing adequate automation to accomplish most corrective actions (other than equipment repair or replacement) without manual intervention, (3) assuring that the timing coordination is available at any node so long as there remains one functioning communications link to that node, and (4) providing a backup mode that will enable continued operation, even though degraded, of any node that cannot continue to coordinate its own clock to the network.

To permit a quick review of the attributes, each has been set off in block format preceding its accompanying discussion. Reasons for the application of each attribute to the DCS are given.

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I. INTRODUCTION

This Engineering Publication is intended to call attention to important applications considerations for timing capability needed by a digital Defense Communications System (DCS).* For planning and engineering, requisites of a specific application are often equally as important as technical items and sometimes more so. For good planning, both technical factors and their specific application must be considered in determining a course of action. Technical possibilities for synchronizing a digital DCS have been discussed previously, where it was shown that providing the attributes presented here for timing in a digital DCS is both technically and economically practical [1,2,3,4]. However, the requisites of the specific application probably were not adequately considered in those previous papers. In particular, they did not demonstrate an adequate appreciation for the differences between the needs of peacetime civilian digital communications networks and worldwide military networks, such as the DCS, which are needed for support of any full-scale war and to satisfy a wide variety of other military requirements. The suggested attributes presented here for timing in a digital DCS are offered for consideration as fundamental needs for such a system. They were generated by giving careful consideration to such wartime requirements of a digital DCS as survivability and the ability to interoperate with other digital communications systems. When they are provided in the DCS, they will contribute greatly to its survivability, and operation at the interface between the DCS and any known existing or planned digital communication system will either be at least as good as operation within that other system or as good as can be achieved without one of the systems becoming dependent on the other. It is believed that with proper planning these attributes can be provided quite economically, and that numerous problems will be avoided if they are included in the development and procurement of new equipment.

*Most of this publication was presented by the author at the Eleventh Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting [5].

II. BACKGROUND

It has become generally accepted that, "...the advantages of digital over analog communications system design for the future were overwhelming..." [6]. Therefore, it is expected that some time in the future, the DCS will predominantly employ digital techniques. Such a digital communications system requires a timing* (synchronization) function in order to be effective. The time relationship of each particular pulse to other pulses in the same sequential stream is fundamental to interpreting the information contained in the pulses. If time division multiplexing is used, this time relationship determines to whom the information belongs and also what it means; i.e., particular time slots are assigned for particular purposes.

In analog communications systems, noise or small errors in either signal amplitude or frequency can cause undesirable but usually tolerable signal degradation, and the same can be said for isolated errors in a digital communications system. However, the loss of proper timing in a digital system is catastrophic. When bits do not fall in their assigned time slots, all received information is meaningless -- a totally unacceptable situation. This characteristic makes the timing/synchronization function one of the most important functions in a digital communications system. Fortunately, correct timing is not difficult to achieve in a simple point-to-point communications system, and there are many different approaches that can provide at least a minimal timing capability for even the most complex digital communications network [1,2]. However, some of these approaches are unacceptable for application in the DCS and those remaining have various degrees of desirability. A set of desired attributes is needed against which the different approaches to timing can be evaluated. This Engineering Publication provides a set of such attributes and explains their importance to the DCS.

One of the most fundamental changes that is going on in the DoD community is the change in perception of the DCS from that of a peacetime system to a communications system capable of supporting full-scale war [6] while still providing the capability to satisfy an increasing variety of other military requirements. In developing desired attributes for the timing/synchronization of a digital DCS, it is assumed that the DCS will not only transition from analog to

* Note: The word timing is used here in the general sense which includes synchronizing as a special case. It implies a wide variety of related meanings including: (a) scheduling; (b) making coincident in time or causing to occur in unison; (c) setting the tempo or regulating the speed; (d) ascertaining the length of time or period during which an action, process, condition or the like continues; (e) causing an action to occur at a desired instant relative to some other action or event; (f) producing a desired relative motion between objects; (g) causing to occur after a particular time delay; or (h) determining the moment of an event.

digital, but also to a network capable of supporting full-scale war. The major difference between a communications system designed for peacetime and one designed for wartime is the need for survivability of sufficient communications capability to make our military forces effective. Survival of the timing function in a digital communications network is essential to survival of the communications function. It also is highly desirable to have an acceptable timing capability available even when the communications function is not available. One reason is that the timing function can be useful for establishing or reestablishing communications. For example, the length of time required to acquire synchronization of a spread spectrum signal that is being jammed, depends on the size of the search window. An acquisition search window of a few milliseconds might require a thousand times longer to acquire synchronization than a window of only a few microseconds. This capability (accuracy of a few microseconds) is already used in the DSCS to permit the acquisition of spread spectrum signals within a reasonable period of time in a jamming environment.

In the past, problems have occurred in the timing relationship between different digital communications networks that were not originally engineered to communicate with one another. In some cases, these problems were overcome by the addition of variable storage buffers and adequate clocks to control them, while in other cases modification of equipments might also be required. Even after these corrective measures, it might sometimes be necessary to interrupt traffic to reset the variable storage buffers. It is not always possible at the time of equipment development to predict just what system interfaces will be required during the lifetime of an equipment. Therefore, design of the equipment to meet a minimum timing compatibility standard is highly desirable for avoiding future problems. Such a timing compatibility standard should follow a well-developed DCS timing plan. This DCS timing plan should satisfy a set of desired DCS timing system attributes such as those presented and discussed in this Engineering Publication.

III. DESIRED TIMING SYSTEM ATTRIBUTES

In this section, a set of timing system attributes for a digital DCS is presented. A discussion of the importance of each attribute to a digital DCS follows its presentation. Parts of the discussion of some of the attributes presented early on will also apply to attributes that follow. This is particularly true of the discussion of the first attribute.

1. REFERENCE TO UTC

> Time and frequency reference information utilized in applicable Federal Government telecommunications facilities and systems shall be referenced to (known in terms of) the existing standards of time and frequency maintained by the U.S. Naval Observatory, UTC (USNO), or the National Bureau of Standards, UTC (NBS).

Discussion: This is a direct quote from FED-STD-1002, and it is DoD policy to comply with Federal Standards. However, different people have chosen to interpret this standard in different ways. The following discussion will illustrate the need for using a standard timing reference and should help to bring out a desirable interpretation of the first attribute as applied to a digital DCS.

Can you imagine trying to make flight connections at a busy airport, such as Chicago's O'Hare, if each airline used only its own clocks, and clock time of each airline differed from that of every other airline? At the least, it would cause considerable unnecessary inconvenience. A century ago, that situation existed in some large railroad stations. You could set your pocket watch to any one of a number of clocks on the station wall, each indicating the official time for its associated railroad line. Problems with this are obvious, but the railroads were heavily criticized when they adopted a standard railroad time in 1883. Standard time slowly gained popularity, and in 1918 Congress passed the Standard Time Act. The advantage of standard time for planning interconnecting flights when using modern air travel is quite obvious. Crossing time zones can cause problems to travelers in keeping track of which time zone applies to their present location. These time zone problems are sometimes alleviated for both travelers and long distance electromagnetic communications by using a worldwide time standard such as coordinated universal time (UTC).

The problems of scheduling the transfer of bits of information from one transmission link to another, where each bit must be made to coincide with its assigned time slot, are somewhat similar to those of transferring passengers from one airline to another. Each is made simpler by well planned and well maintained traffic schedules. However, a major node of the digital communications network will

typically handle many millions of bits each second, and the bits travel between nodes at speeds approaching the speed of light. As with the passenger trains, it is not necessary that all clocks read the same (bits can be stored in buffers just as passengers can be stored in depots), but it is obviously highly desirable; and whereas tolerances of a few minutes were acceptable for the railroads, tolerances of a few microseconds are desirable for a high capacity digital communications network. Corrective action for an information bit that misses its assigned time slot might be even more difficult than corrective action for a passenger who misses an assigned aircraft flight. Unlike the airline passenger, a single communications bit that misses its time slot assignment is likely to cause those that follow to miss theirs also.

Whenever a new comunications system is planned, the system planners seem to quickly arrive at the conclusion that it is only important to provide synchronism within their own system -- that they do not have to worry about other systems that are being planned. Does that not sound like those old railroads where each had its own time? Like the railroads, each can be made to work, but also like the railroads, taken together they present problems that can easily be avoided by using a standard time system.

In the past, this country's largest telephone company has provided for its own digital synchronization needs as it saw those needs, and interfacing companies had to accept timing from that company. Although that policy has not changed, present planning is to eventually reference that company's atomic clocks to the National Bureau of Standards. What is wrong with an approach where one telephone company provides a timing reference for all of the others? First, there are two U.S. Government organizations charged with keeping standards of time and frequency - the National Bureau of Standards and the Naval Observatory. Master clock time at each of these organizations is in close agreement with Coordinated Universal Time as determined by the Bureau International de l'Heure, to which both of these U.S. Government organizations contribute timing information. Second, although smaller U.S. telephone companies might be willing to accept their timing reference from the largest U.S. telephone company, the likelihood of this occurring internationally is much smaller -- an international time standard should be used. Third, as now being implemented by telephone companies, their synchronization system permits time delays to accumulate as the timing information is passed through the system, and in some cases individual local clock errors also can accumulate through long tandem connections. This means that clocks in different parts of the network have somewhat different time (or phase), although clocks at adjacent nodes are within acceptable (bufferable) tolerances. Although this is quite satisfactory for civilian digital communications, it is quite likely that it could not be tolerated by some future military systems.

The functional division between digital communications and computation by digital computer is becoming less distinct, as well as that between communications and navigation or position location. For these relationships to be mutually beneficial, all should be based on common time standards. From a wide variety of viewpoints, the digital networks of the DCS should fully comply with a restrictive interpretation of FED-STD-1002.

2. SPECIFICATION OF TOLERANCES IN TIME OR CONTINUOUS PHASE

> Timing tolerances (clock errors) at major nodes of digital DCS networks should be specified in time (microseconds) or continuous phase (degrees -- not modulo 360) rather than frequency.

Discussion: Relating this to the previous example of making connections between flights at busy airports, it is not enough to have the clocks for all airlines running at the same rate; they should also indicate nearly the same time. In digital communications, the timing/synchronization system is used for assigning individual communications pulses to specific time slots. For this to be effective, tolerances should be established on the location (in time or phase) of the time slot and also on the arrival time (or phase) of the assigned pulse. Received bits should be retimed by temporarily storing them in variable storage buffers from which they are removed at the proper time as determined by the local clock. If the local clock pulse is not at exactly the right time, it will be either early or late by a certain phase angle at the pulse repetition rate; or, alternatively, early or late by a certain amount of time (in microseconds). A timing tolerance stated in microseconds is normalized, which makes it convenient to apply to any of a large number of data rates likely to be encountered throughout the communications system. The size of the variable storage buffer determines the ability to accomodate early or late arrival of pulses relative to the local clock. The phase (or time) tolerances of the local clocks and the bit rate of the communications stream along with expected variations in signal path delays determine the necessary size of the buffers.

There is no simple way that these timing errors (the ones of basic significance to the digital communications timing system) can be stated as frequency errors (Hertz) or fractional frequency errors. However, because of the relationship between phase angle and frequency (frequency is the time derivitive of phase angle), the phase angle error at any time can be determined from an initial phase angle error plus the time integral of the frequency error from the time of the initial phase error to the time of the measurement of interest. In order for the phase angle (or time) error to be bounded, the average frequency error must be zero. Any nonzero average frequency error will eventually result in an unacceptable phase error; i.e., it will eventually require interruption of the

communications traffic to reset the variable storage buffers to prevent them from either emptying or overflowing.

It is probable that the integral relationship between frequency and phase together with the traditional approach of specifying frequency tolerances in analog systems has resulted in attempts to specify digital synchronization in terms of frequency. If the allowable phase (or time) tolerance has been specified, average frequency errors that will permit that tolerance to be maintained for a specific time can be determined. In general, relatively high errors can be accepted in the pulse rate for a short period of time. As an example, assume that the pulse frequency in a system which initially has no phase error, is 1 percent low over a period of five pulses, and then is 1 percent high for the following five pulses. After the first five pulses, there will be a phase (or time) error equal to 5 percent of the pulse period -- a normally acceptable value -- and after the second five pulses (a total of ten pulses) the error will be zero again. Now as a further example, assume that the frequency had been high for five billion pulses instead of only five pulses and then low for another five billion pulses. Then, if the maximum phase (or time) error were not to exceed 5 percent of the pulse period, the frequency error could only be one billionth of 1 percent. In both examples, the phase (or time) error is the item of predominant interest, and the frequency error is of interest only because of its relationship to the phase (or time) error.

3. FREEDOM FROM DEPENDENCE ON ANY PARTICULAR FACILITY

> The timing/synchronization function in the DCS should not be solely dependent on the continued operation of any particular network node, transmission link, or any facility external to the network.

Discussion: Since nodes of the DCS and the transmission links interconnecting them are subject to enemy destruction or electromagnetic jamming attack in addition to natural disaster and other harmful events, it is obviously desirable to construct the timing system to minimize the impact that the loss of any link or node, or any combination of links and nodes, would have on the timing function for the surviving portions of the network. No specific nodes or links in the network should have such individual importance to the network timing function that a successful enemy attack on them would seriously degrade the network timing. No specific parts of the timing system either within or external to the communications network should appear to be particularly attractive targets to an enemy. This implies that control of the timing system should be distributed rather than centralized.

4. SELF-ORGANIZATION

> Following the loss of any node or transmission link of significance to the timing function, either through failure or enemy action, the timing system for the DCS should automatically reorganize itself into an optimal configuration for the surviving elements to continue to provide the desired timing function.

Discussion: For any communications network timing approach, there is either some optimum hierarchy of the links and nodes, or some optimum set of parameters for providing a stable system, or both. When links or nodes of the network are lost, adjustments to the network (which might include partitioning or reconfiguration) should be made to assure that degradation of the timing function is acceptably minimized. In civilian peacetime systems, where the need for such adjustments only results from occasional equipment failures or rare acts of nature, it is acceptable to make the necessary adjustments manually, and necessary repairs to the failed equipment could be expected to be made promptly. However, in a wartime situation, extensive damage to the military communications system due to enemy action might simultaneously occur in many widely separated areas. The maintenance and repair function might be intentionally or unintentionally impeded by enemy action. Access to areas where repairs are needed might be severely restricted, and required skilled personnel might not be available when needed. Therefore, the timing/synchronization system for a military communications system should be highly automated. In particular, the reorganization of the timing system following the loss of any link or node of the communications system should be totally automatic; and by attribute number 3, it should also be distributed rather than centralized.

5. AVAILABILITY OF TIMING SO LONG AS COMMUNICATIONS SURVIVE

> So long as any communications link to a node survives, it should be capable of supporting the timing function.

Discussion: Unlike a civilian communications system where failures in the timing system can be expected to be random and infrequent, sudden massive destruction of many parts of the wartime military communications system can be expected over a short period of time. Whereas a couple of backup paths would be quite adequate to assure timing at a particular node in the peacetime civilian system, it might not be unusual to lose all but one communications link to a major node (or even several nodes) in a wartime military system. Since it is not possible to assure which link might remain intact following such an attack, every link must be capable of supporting the timing function.

6. ABILITY OF NODES TO RAPIDLY REENTER THE NETWORK

> A node temporarily disconnected from the network should have the timing capability to rapidly reenter the network -- including the capability for rapid synchronization of spread spectrum or other broad bandwidth digital signals in a jamming environment.

Discussion: Under jamming conditions, the length of time required to test a given timing relationship to determine whether or not it is in synchronization is greatly increased. If 1 second of sampling time is required to make a decision between being in synchronization or out of synchronization for each 10 nanoseconds change in timing, an uncertainty window of 10 microseconds could require a total of 1000 seconds to search. If correct synchronization were not found the first time through, the window would have to be searched again. Obviously, the amount of search time required depends upon the design of the system and the environment in which it must function, but it is desirable to maintain a small search window for acquiring or reacquiring synchronization in a military communications system which is subject to enemy jamming. In addition to speeding up the synchronization process for spread spectrum equipment, good system timing can also be used to speed the synchronization of multiplexing and cryptographic equipment. This reduces the amount of time the equipment is out of synchronization following signal outages, thereby minimizing the loss of communications traffic.

7. DISTURBANCES NOT PROPAGATED

> To the extent practicable, disturbances in the clocks at individual nodes of the network should be prevented from propagating to other nodes of the network.

Discussion: Errors as a result of disturbances at remote clocks propagating to the local clocks use up a portion of the available phase tolerance at the local node and make it more susceptible to loss of synchronization from other causes. This includes an overall reduction in the stability of the timing system, making it less capable of accommodating signal fades and other transmission disturbances. This attribute is particularly important if the disturbance occurs just prior to the time when a node enters a backup free-running mode of operation where an induced frequency error will be integrated over a long period of time producing a very large phase error. This attribute provides increased resistance to both enemy attack and other perturbations.

8. AVOIDANCE OF TRAFFIC INTERRUPTION TO RESET BUFFERS

> A normally operating timing system should not require interruption of traffic solely for resetting variable storage buffers to accommodate errors in uncoordinated system clocks.

Discussion: Planners of several civilian digital communications systems in North America considered the use of accurate free-running clocks with provision for occasional interruption of traffic to reset variable storage buffers [7]. All of these system planners rejected this approach because they felt that it would be unacceptable to their customers. It is even less desirable in a military system where there are additional functions, such as encryption and spread spectrum transmission, which require synchronization. The worldwide nature of a military network such as the DCS precludes a low traffic nighttime period for such interruptions because the sun never sets on such a worldwide network.

9. CAPABILITY FOR MOST EFFECTIVE USE OF FREE-RUNNING MODE

> Capability to reset variable storage buffers with minimum interruption of traffic should be provided in order to permit continued communications by operating in a free-running mode whenever means for clock coordination is not available.

Discussion: A free-running mode is a last ditch backup mode of operation to permit continued communications (although degraded because of required interruptions) if all means of clock coordination at a node should be lost while at least one communications link is otherwise intact. In a well designed system, it should be a very rare occasion when this mode of operation would be required, but it would be shortsighted not to provide this capability. The timing system should not be permitted to be the sole reason for communications not being available. This attribute could be very important should it be needed when continued communications are critical.

10. SYSTEMATIC SELF-MONITORING

> Systematic self-monitoring of the timing function should be provided.

Discussion: The timing function in a digital DCS must be designed to be very reliable. Under normal operating conditions, undisturbed by hostilities, failures will occur very rarely. Under these conditions, it will be very difficult to maintain well trained, experienced personnel for servicing failures to the timing system.

Because of this, it is important that the timing system provide automatic self-monitoring and fault diagnosis. It is desirable that such monitoring include the monitoring of the actual timing function in addition to normal power-supply voltage measurements and signal level measurements. Many types of failures that can affect the operation of a timing system can only be detected by monitoring the actual timing function. It is also important to detect pending timing failures long before any interruptions to communications traffic occur. Trend information and automatic statistical evaluation of systematic self-monitoring of the timing function can be used to automatically provide early detection of problems and self-diagnosis of their causes. This information can then be used to automatically indicate the needed corrective action.

11. OPEN OPTIONS

> Options with potential importance for satisfying future timing requirements should not be precluded without good reason.

Discussion: It is a common occurrence that inadequate planning for future needs finally results in a situation requiring either (1) a very large expenditure of funds or (2) foregoing the service. When it arises, this situation always seems to be unexpected because it was not included in the original planning. Sometimes the capability could have been provided at no extra cost at the time of original equipment development, and nearly always at a small fraction of the cost for retrofit after the equipment is fielded. It is difficult to predict at the time of equipment development all of its applications during its lifetime. Therefore, it is very desirable to leave open all options that might make it possible to satisfy those unpredicted applications as they arise, unless this results in some significant penalty, e.g., significant additional costs. System planners should specifically investigate whether their plans unnecessarily close off future options.

IV. CONCLUSIONS

A set of attributes for timing in the digital DCS has been presented. These attributes provide for keeping major nodes of the DCS within acceptable phase tolerances of one another by automatically coordinating all of their phases with the standard provided by the U.S. Naval Observatory, UTC (USNO), or the National Bureau of Standards, UTC (NBS), whenever either is available. If UTC is not available, a particular clock within the network is automatically selected as a reference for the rest of the network. Survivability of the network is further enhanced by the following: (1) assuring that it is not dependent on any one point of centralized or concentrated vulnerability to enemy action, (2) providing adequate automation to accomplish most corrective actions (other than equipment repair or replacement) without manual intervention, (3) assuring that timing coordination is available at any node so long as there remains one functioning communications link to that node, and (4) providing a backup mode which can continue to provide operation (although degraded) of any node that loses is ability to coordinate its clock. Any improvement in stability and accuracy through improved clock disciplining procedures will further enhance a system's capability to provide all of these attributes under all conditions likely to occur in a full-scale war.

By injecting the timing system attributes presented here into the development and procurement of new equipment, the capability of a digital DCS to survive and effectively support full-scale warfare will be greatly enhanced. It is believed that with proper planning, these attributes can be provided economically; and that these attributes can preclude many potential problems.

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